(54) Title: ACQUISITION OF 3-D SCENES WITH A SINGLE HAND HELD CAMERA

(57) Abstract: The acquisition of 3-D scenes by a single hand-held camera is disclosed. The camera is preferably mounted on a lens attachment with four mirrors, enabling stereo capturing of the scene. The signal processing tasks involved, camera calibration and correspondence estimation, are each disclosed. Both fixed and self-calibration methods benefit from the use of the lens attachment to acquire a scene. Specifically, full self-calibration of the camera is enabled, without loss of absolute scale as seen in prior art stereo self-calibration methods. Accurate 3-D models are obtained with the method of the invention.

ACQUISITION OF 3-D SCENES WITH A SINGLE HAND HELD CAMERA

REFERENCE TO RELATED APPLICATIONS

This application claims an invention which was disclosed in Provisional Application Number 60/138,965 , filed June 11, 1999 , entitled "ACQUISITION OF 3-D SCENES WITH A SINGLE HAND HELD CAMERA". The benefit under 35 USC §119(e) of the United States provisional application is hereby claimed, and the aforementioned application is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The invention pertains to the field of cameras. More particularly, the invention pertains to hand-held cameras and the acquisition of three-dimensional scenes.

DESCRIPTION OF RELATED ART

Stereographic photography is the method of producing images which are apparently three-dimensional by recording separate left- and right-eye images. The viewer reconstructs the 3-D image by viewing the two separate 2-D images simultaneously. Stereographic photography has been known since at least the late 19th century, when stereo viewers were a popular parlor accessory.

Such stereo views have historically been created with two lenses on a single camera, spaced apart by approximately the inter-ocular distance of a human head. The Stereo Realist™ series of 35mm still cameras, popular in the 1950's, are an example of this kind of imaging. Left and right views were recorded simultaneously through two lens/shutter sets on alternate frames of the 35mm film. The later Nimslo™ system used four lenses for essentially the same approach.

Stereo movies appeared in the 1950's. The images were typically created either using two synchronized cameras, or a two-lens system on a single camera. Similarly, the

various Stereo TV systems have typically used two cameras (see Lipton, et al, US Patent 4,583,117) or a single camera with two lenses (Lipton, et al, US Patent 4,523,226).

In the area of 3-D scene acquisition by stereo equipment, two signal processing tasks are involved: calibration of the camera pair [1] and estimation of corresponding pixels in the image pair [5].

In the area of camera calibration, there are two different techniques: fixed and self-calibration. In fixed calibration, all camera parameters are extracted off line by placing a special object with known geometry in front of the cameras and processing of the camera images [1, 2]. This method provides very accurate and complete results (all parameters are obtainable). Additionally, calibration reduces correspondence estimation from a 2-D search problem to a more efficient and reliable 1-D search [5].

However, fixed calibration suffers from a number of disadvantages. A special calibration object and user interaction is required. Each time the camera parameters change, e.g. due to zooming or change of convergence angle, the calibration has to be repeated.

Self-calibration circumvents these disadvantages. In this method, the correspondences are estimated first, in an image pair of the scene. After this, the camera parameters are extracted from the found correspondence field [4]. The price to be paid is two-fold. First, correspondence estimation is a more demanding task since no reduction from a 2-D to a 1-D search can be applied. Secondly, in self-calibration methods with normal stereo camera pairs, there is no reference to the standard SI meter. Thus the scale of the 3-D models is not obtainable by the prior art methods [3].

SUMMARY OF THE INVENTION

The acquisition of 3-D scenes by a single hand-held camera is disclosed. The camera is preferably mounted on a lens attachment with four mirrors, enabling stereo capturing of the scene. The signal processing tasks involved, camera calibration and correspondence estimation, are each disclosed. Both fixed and self-calibration methods benefit from the use of the lens attachment to acquire a scene. Specifically, full self-

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calibration of the camera is enabled, without loss of absolute scale as seen in prior art stereo self-calibration methods. Accurate 3-D models are obtained with the method of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

5   Fig. 1 shows an example of an apparatus of the present invention.

Fig. 2 shows the function of the mirrors in the apparatus of the present invention.

Fig. 3 shows a stereo camera model.

Fig. 4 shows a complete scheme of acquisition according to the present invention.

Fig. 5a shows an image of the calibration plate of the present invention.

10   Fig. 5b shows an image of an actual scene according to the present invention.

Fig. 6 shows a rectified image pair according to the present invention.

Fig. 7 shows a disparity field according to the present invention.

Fig. 8 shows a 3-D model according to a method of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

15   The acquisition of 3-D scenes with a very specific stereo camera is disclosed. Using camera calibration parameters, two light rays originating from a pair of corresponding pixels are constructed. The intersection of the two rays then provides the 3-D coordinates of a scene point.

        The apparatus is shown in Fig. 1. A single hand held camera (1) is mounted on a
20   lens attachment (2) with mirrors as disclosed in U.S. Patents 5,532,777, 5,828,913, and 5,883,662, the disclosures of which are herein incorporated by reference [7-9]. Briefly, the lens attachment preferably has a set of four mirrors in two pairs located in front of a camera lens. The outer two mirrors (6) and (7) face generally outward along the optical axis of the lens and the inner two mirrors (3) and (4) face generally inward into the lens.

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The centers of the outer two mirrors (6) and (7) are spaced apart by an appropriate interocular distance. The two inside mirrors (3) and (4) are together large enough to cover the complete viewing area of the lens, each taking exactly half of the lens viewing area. The two outside mirrors (6) and (7) are preferably bigger than the inside pair of mirrors (3)

5   and (4) and large enough to cover the viewing area of the inside pair of mirrors (3) and (4) to avoid viewing area reduction. The convergence of the two outer mirrors (6) and (7) is adjustable by swiveling them simultaneously and equally about their centerlines with a ganging mechanism. The two center mirrors (3) and (4) may be fixed, or could be adjustable by being swiveled so that one side of each remains in tight contact with the

10   other along the optical axis of the camera lens, and each makes a 45° or lesser angle to the optical axis.

Imagine that the directions of the incoming light rays (5) are reversed, then the two center mirrors (3) and (4) split the bundle of light rays (5) from the camera in two parts. The two side mirrors (6) and (7) redirect each bundle towards the scene (8). The

15   convergence point (9) of the two bundles is adjustable by rotation of the side mirrors (6) and (7). The image (10) is also shown.

The small size and low weight of this stereo camera provide high user mobility. In addition, the use of a single camera is economical and does not require shutter synchronization of a camera pair. For storage, only one conventional recorder is needed.

20   Both the calibration and correspondence estimation tasks benefit from this particular setup.

Correspondence estimation is based on photometric similarity of corresponding pixels. Photometrically unbalanced stereo cameras are a cause of errors, which is avoided to a large extent by the use of a single camera. As discussed in the background, there are

25   two different calibration techniques: fixed and self-calibration. Both of these types of calibrations benefit from the apparatus shown in Fig. 1. In prior art self-calibration methods with normal stereo camera pairs, there was no reference to the standard SI meter. Thus the scale of the 3-D models were not obtainable [3]. The known geometry of the apparatus of the present invention provides the scale. The use of a single camera in

concert with the lens attachment simplifies the stereo camera model without loss of generality.

STEREO CAMERA MODEL

The camera model for the device is a novel version of the general model for stereo cameras in [4]. Fig. 2 shows the function of the mirrors (13), (14), (16) and (17) in the lens attachment. The single real camera (11) is split into two virtual cameras (12) and (15), each with half of the original CCD chip. The half CCDs are not centered on the optical axes (20) and (21) of the virtual left (12) and right cameras (15). The rotation of the two side mirrors (16) and (17) is mechanically coupled. To have any overlap in the two virtual camera images, $\alpha = 45° + \Delta\alpha$, with $\Delta\alpha > 0$. If the side mirrors (16) and (17) are rotated around point P and Q, the two virtual cameras (12) and (15) rotate around the same points with double speed.

Fig. 3 shows the general stereo camera model from [4]. Five reference frames are defined, the stereo frame (22), the left/right lens frames (23) and (24) and the left/right projection frames (25) and (26). The camera baseline is B. The frame SF (22) is defined to be a right handed frame in which the two optical centers lie on the x-axis symmetrically around the origin, at $(-\frac{1}{2}B, 0,0)$ for the left camera and $(+\frac{1}{2}B, 0,0)$ for the right camera, in SF coordinates. From Fig. 2, it is deduced that:

$$B = 2w + 2(h + w)\sin 2\Delta\alpha + \varepsilon_0 \quad (1)$$

relating meters to angles. This provides a means for self-calibration in meters, instead of unknown units. The ε_0 models remaining imperfections, and is assumed to be small.

The orientations of the left and right lens frames are defined by two sets of Euler angles (φ_x, φ_y, φ_z). The lens is present in the origin of the lens frames LF-L and LF-R, oriented in their xy planes. Radial symmetry in the lenses is assumed. At this point, the angle φ_z has no meaning. Instead of discarding φ_z, it is used for the orientation of the CCD. The reference frame SF (22) is defined up to a rotation around the x-axis. An arbitrary equation is introduced that eliminates either $\varphi_{x;L}$ or $\varphi_{x;R}$, such as $\varphi_{x;L} + \varphi_{x;R} = 0$.

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Ideally, both are zero, but due to imperfections in the apparatus and the hand-cam this might not be the case:

$$\varphi_{x;L} = \varepsilon_1, \varphi_{x;R} = -\varepsilon_1 \qquad (2)$$

For the $\varphi_{y;L}$ or $\varphi_{y;R}$ ideally $\varphi_{y;L} = 2\Delta\alpha$ and $\varphi_{y;R} = -2\Delta\alpha$. Allowing for small imperfections:

$$\varphi_{y;L} = 2\Delta\alpha + \varepsilon_2, \varphi_{x;R} = -2\Delta\alpha + \varepsilon_3 \qquad (3)$$

It is assumed that the CCD is perfectly flat and has perfectly perpendicular image axes. The image formation is invariant for scaling of the triplet focal length, horizontal and vertical pixel size. Therefore, without loss of generality, the horizontal size of the pixels are chosen to be equal to 1 and the vertical size equal to R, the pixel aspect ratio. The positions of the projection frames $PF_{L/R}$ (total CCD chip) relative to the lens frames $LF_{L/R}$ are defined by a single vector $O_{PF}^{X_{LF}}, O_{PF}^{Y_{LF}}, O_{PF}^{Z_{LF}}$ since they refer to the same physical camera. The first two numbers define the intersection of the lens optical axis with the total CCD (mis-positioning) and the third is the focal length f:

$$O_{PF}^{X_{LF}} = \varepsilon_4, O_{PF}^{Y_{LF}} = \varepsilon_5, O_{PF}^{Z_{LF}} = f \qquad (4)$$

Since a change of focal length in cameras is usually performed by movement of the lens rather than the CCD chip, h is modeled in (1) as a linear function of f:

$$h = a + bf \qquad (5)$$

a and b are parameters estimated to establish a relationship between w and h. The orientation of the projection frames $PF_{L/R}$ (total CCD chip) relative to the lens frames $LF_{L/R}$ is defined by a single set of Euler angles (θ_x, θ_y, θ_z). θ_z *relates* to the rotation of the projection frame. This is already modeled with φ_z and thus $\theta_z = 0$ is used.

For the φ_z:

$$\varphi_{z;L} = \varepsilon_6, \varphi_{z;R} = \varepsilon_7 \qquad (6)$$

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The θ_x and θ_y model the non-orthogonal CCD placement with respect to the optical axis. Thus:

$$\theta_x = \varepsilon_8, \theta_y = \varepsilon_9, \theta_z = 0 \quad (7)$$

Since mispositioning and misorientation of the CCD is incorporated in equations (4) and (7), lens distortion can be modeled more simply than in [6]. The radial distortion parameter K_3 is used:

$$K_3 = \varepsilon_{10} \quad (8)$$

The stereo camera model preferably contains the following parameters. For fixed calibration, there is a baseline B, a convergence angle $\Delta\alpha$, a focal length f, a pixel aspect ratio R and ten error parameters $\varepsilon_1 \dots \varepsilon_{10}$ which are assumed to be small.

For self-calibration, the baseline B is discarded from the model by setting it to 1 during the calibration [4]. Afterwards, it can be obtained by equation (1), provided that w, a and b have been determined before hand.

ACQUISITION SCHEME

Fig. 4 shows the complete scheme of acquisition. First, the hand-cam is mounted on the lens attachment. Then, a fixed calibration is performed for several values of convergence angle $\Delta\alpha$ and focal distance (zoom) f in order to obtain a, b and w. In addition, life-time constants such as the pixel aspect ratio R are obtained. The constants obtained will be invariant during the recording of the actual scene.

Then the scene is recorded, during which any change in convergence angle and zoom are allowed. Afterwards, the sequence is processed according to the left route in Fig. 4. After correspondence estimation, self-calibration is applied [4]. The invariant (1) then enables 3-D model acquisition with the correct scale.

Experiments

A digital photocamera that takes 1024 x 768 images in JPEG format was used. Fig. 5a shows images of the calibration plate (30) and Fig. 5b shows images of the actual scene

(31). Several fixed calibrations were performed, with different values of the convergence angle and focal distance. With the different values for B, f and $\Delta\alpha$, a least squares technique was applied to estimate w, a and b.

With the parameters from the fixed calibration, a good 3-D model was obtained from the scene image (31) in Fig. 5b. After splitting the scene image in a left and right image pair, the images were rectified [5], as shown in Fig.6. All correspondences lie now on equal scan lines and 1-D disparity estimation was performed. A Markov Random Field disparity estimator [5] was used to obtain the disparity field shown in Fig. 7. After triangulation of all corresponding pixel pairs, the 3-D model (40) was obtained. Fig. 8 shows the details in the facial area.

The acquisition of 3-D scenes with a special device [7] enables stereo vision by a single hand-held camera (see Fig. 1). This system has several advantages. It is small and thus provides high user mobility, it needs only a single conventional recorder for storage and the use of a single camera is economical.

Both camera calibration and correspondence estimation benefit from the device. Correspondence estimation relies on photometric similarity between corresponding pixels. With this device, there are no photometrical differences between left and right cameras. Further, left and right shutter synchronization is guaranteed by definition. For camera calibration, it was shown that a simpler stereo camera model could be used since the virtual left and right cameras share some physical properties from the single real camera. In addition, the device allows for self-calibration methods, while still providing a means for the capturing of absolute scale.

The experiments showed that good 3-D models are obtained with the device. Currently the preferred method is a fixed calibration method, although a self-calibration method is also possible. The camera parameters obtained were well suited for the acquisition of a 3-D model.

Accordingly, it is to be understood that the embodiments of the invention herein described are merely illustrative of the application of the principles of the invention. Reference herein to details of the illustrated embodiments is not intended to limit the

scope of the claims, which themselves recite those features regarded as essential to the invention.

REFERENCES

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[7] P.O. Zanen, "Single lens apparatus for three-dimensional imaging having focus-related convergence compensation", US Patent No. 5,532,777, July 2, 1996.

[8] P.O. Zanen, "Method for three dimensional measurement and imaging having focus-related convergence compensation", US Patent No. 5,828,913, October 27, 1998.

[9] P.O. Zanen, "Apparatus for three dimensional measurement and imaging having focus-related convergence compensation", US Patent No. 5,883,662, March 16, 1999.

What is claimed is:

1. A method of acquiring a three-dimensional scene using a single hand held camera
   having a lens, attached to a lens attachment comprising a right and a left inner
   mirror, both inner mirrors being located in front of the lens facing inwardly along
   an optical axis of the lens toward the lens, covering substantially all of a field of
   view of the lens, the inner mirrors being connected together at one edge at the
   optical axis of the lens, such that the two inner mirrors form an acute angle
   symmetrical about the optical axis of the lens, a right and a left outer mirror, both
   being larger than the inner mirrors and located outward of the inner mirrors, facing
   outward toward the subject, such that substantially all of the field of view of the
   inner mirrors is covered by the outer mirrors, the outer mirrors being pivotable
   about a vertical axis, a ganging mechanism for simultaneously pivoting the outer
   mirrors about their vertical axes in opposite senses, having a control input for
   actuating the ganging mechanism, such that a movement of the control input
   causes the right and left outer mirrors to pivot equally, oppositely and
   simultaneously, such that a movement of the control input in one direction causes
   the fields of view of the outer mirrors to converge, and a movement of the control
   input in the opposite direction causes the fields of view of the outer mirrors to
   diverge, and an adapter for moving the control input of the ganging mechanism in
   response to actuation of a focusing means of the lens, connected to the control
   input of the ganging mechanism and the focusing means of the lens, such that
   when the lens is focused at a selected distance, the field of view of the outer
   mirrors converges at the selected distance, comprising the steps of:

   a) deriving values for a, b, and w by performing a fixed calibration for at
      least one value of a convergence angle ($\Delta\alpha$) and at least one focal
      distance (f) wherein w is defined as a distance between an optical
      center of the single hand held camera and an optical center of each
      of the virtual cameras, and a and b are parameters estimated to
      establish a relationship between w and h, wherein h is a distance
      between the optical center of the single hand held camera and an
      intersection of the two inner mirrors;

31   b) recording an image of a scene using the single hand held camera and the
32   lens attachment;

33   c) processing the recorded image using the life-time constant, the value for
34   the convergence angle ($\Delta\alpha$) and the focal distance (f); and

35   d) storing a processed three-dimensional image.

1   2. The method of claim 1, wherein step (a) further comprises the steps of:

2   i) recording at least one calibration plate;

3   ii) splitting an image of the calibration plate into a left image and a right image;

4   iii) detecting the calibration plate; and

5   iv) calibrating the calibration plate.

1   3. The method of claim 1, wherein step (c) further comprises the steps of:

2   i) splitting the image of the scene into a left image and a right image;

3   ii) performing correspondence estimation on the left image and the right image;

4   iii) performing self-calibration; and

5   iv) performing triangulation.

1   4. The method of claim 1, further comprising the step of calculating a relationship
2   between meters and angles using an equation $B = 2w + 2(h + w)\sin 2\Delta\alpha + \varepsilon_0$
3   wherein B is defined as a camera baseline, and ε_0 is defined as an error parameter.

1   5. The method of claim 1 further comprising, prior to step (b), the step of defining five
2   reference frames.

1   6. The method of claim 5 wherein the five reference frames comprise:

2   a) a stereo frame;

3   b) a left lens frame;

4   c) a right lens frame;

5   d) a left projection frame; and

6   e) a right projection frame.

1   7. The method of claim 6 wherein an orientation of the left and right lens frames are

2   defined by two sets of Euler angles $(\varphi_x, \varphi_y, \varphi_z)$.

1   8. The method of claim 7, further comprising the step of introducing an equation that

2   eliminates either $\varphi_{x;L}$ or $\varphi_{x;R}$.

1   9. The method of claim 8, wherein the equation is $\varphi_{x;L} + \varphi_{x;R} = 0$.

1   10. The method of claim 8, wherein when the Euler angles are not equal to zero,

2   additional equations $\varphi_{x;L} = \varepsilon_1, \varphi_{x;R} = -\varepsilon_1$ are used, such that ε_1 is a small error

3   parameter.

1   11. The method of claim 10, further comprising the step of calculating the equations

2                $\varphi_{y;L} = 2\Delta\alpha + \varepsilon_2, \varphi_{x;R} = -2\Delta\alpha + \varepsilon_3$.

1   12. The method of claim 6 wherein a position of the left and right projection frames

2   relative to the left and right lens frames are defined by a single vector

3                $O_{PF}^{x_{LF}}, O_{PF}^{Y_{LF}}, O_{PF}^{Z_{LF}}$ wherein $O_{PF}^{X_{LF}}$ and $O_{PF}^{Y_{LF}}$ define an intersection of a lens optical

4   axis with a total CCD and $O_{PF}^{Z_{LF}}$ is equal to the focal length f.

1   13. The method of claim 1, further comprising the step of calculating a distance h

2   between an optical center of the single hand held camera and an intersection of the

3   inner mirrors using the equation $h = a + bf$.

1   14. The method of claim 6 wherein an orientation of the left and right projection frames

2   relative to the left and right lens frames is defined by a single set of Euler angles

3                $(\theta_x, \theta_y, \theta_z)$.

1   15. The method of claim 14, wherein θ_x and θ_y model the non-orthogonal CCD placement
2   with respect to an optical axis such that $\theta_x = \varepsilon_8, \theta_y = \varepsilon_9, \theta_z = 0$ where ε_8 and ε_9 are
3   defined as error parameters.

1   16. The method of claim 14 wherein θ_z relates to a rotation of the projection frame.

1   17. The method of claim 1, further comprising the step of calculating a radial distortion
2   parameter K_3 using the equation $K_3 = \varepsilon_{10}$, where ε_{10} is defined as an error
3   parameter.

1   18. The method of claim 1, where a plurality of parameters in step (a) further comprise a
2   baseline B, a pixel aspect ratio R and ten error parameters, $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_5, \varepsilon_6, \varepsilon_7, \varepsilon_8,$
3        $\varepsilon_9,$ and ε_{10}, which are each assumed to be small.

1   19. The method of claim 1, further comprising the step of self-calibrating the scene using
2   a plurality of parameters including a baseline B equal to 1, a convergence angle
3        $\Delta\alpha$, a focal length f, a pixel aspect ratio R and ten error parameters, $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_5,$
4        $\varepsilon_6, \varepsilon_7, \varepsilon_8, \varepsilon_9,$ and ε_{10}, which are each assumed to be small.

1   20. A three-dimensional scene created by the method of claim 1.
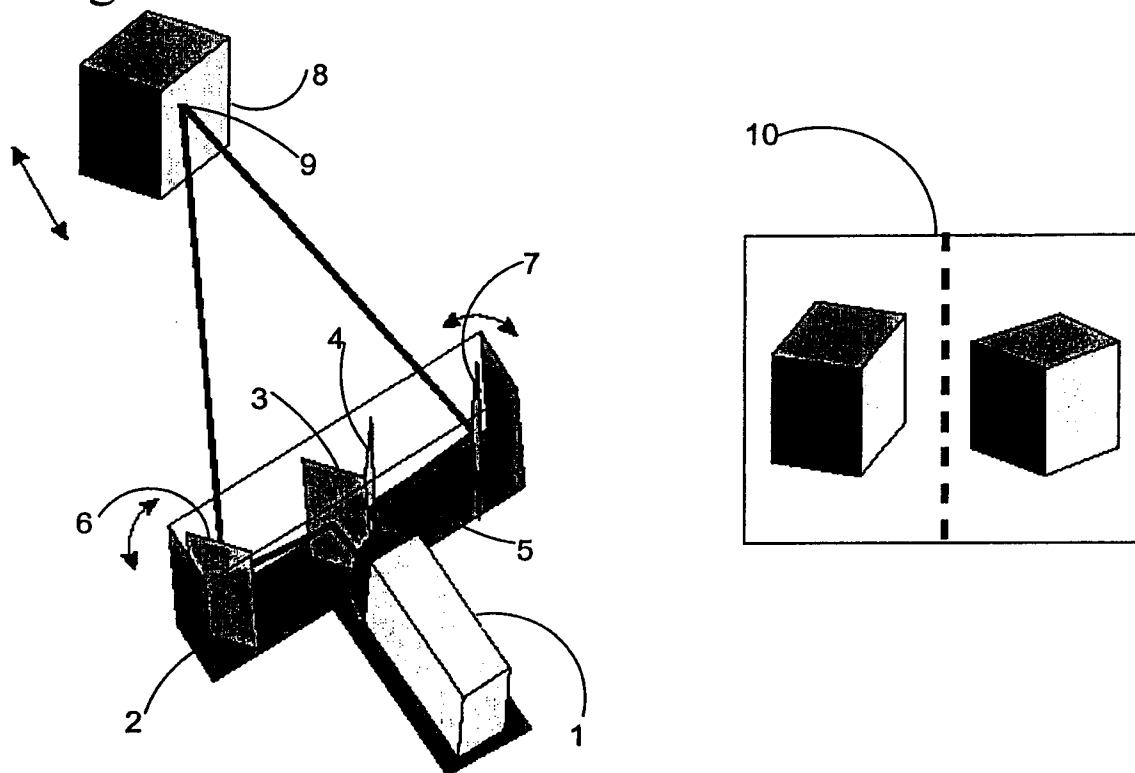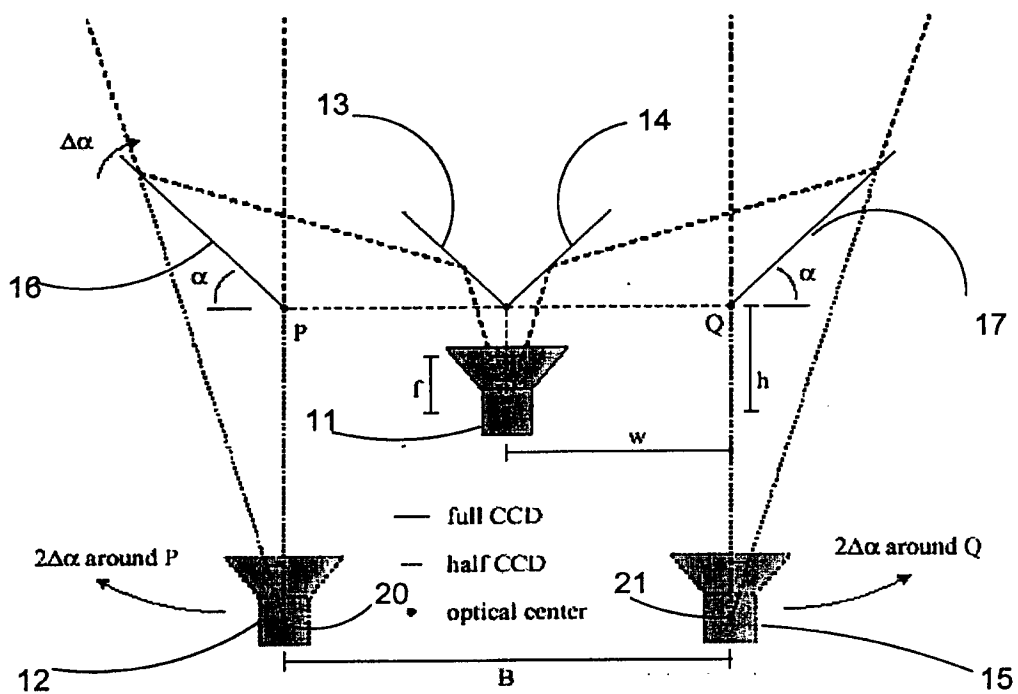
Fig. 1
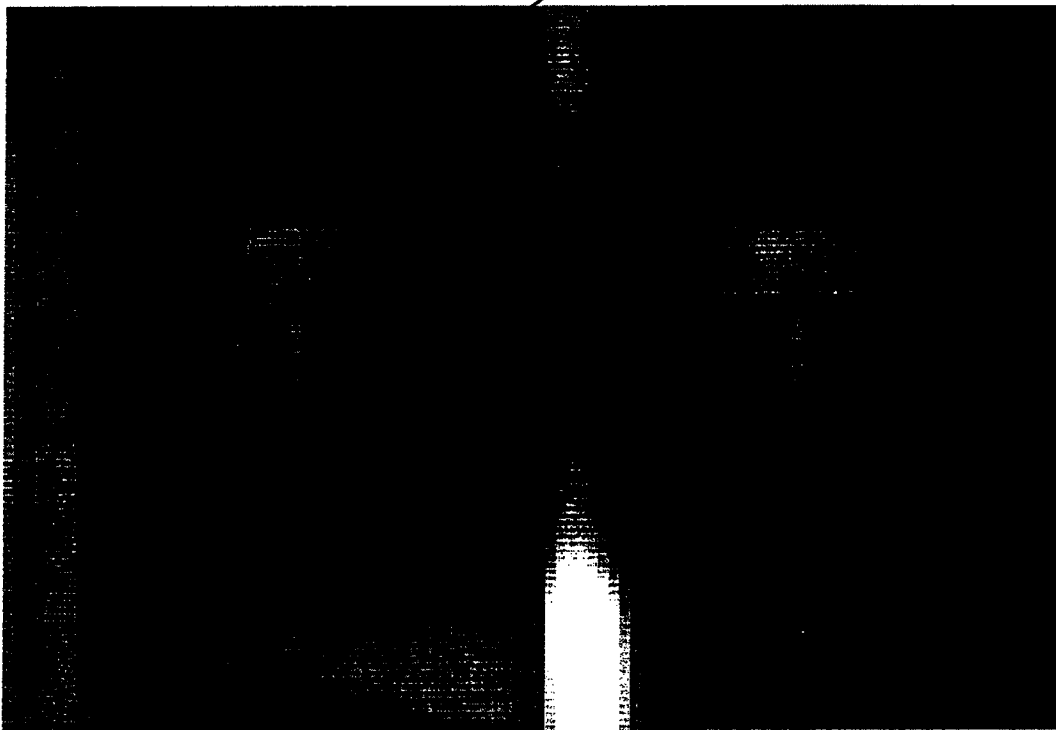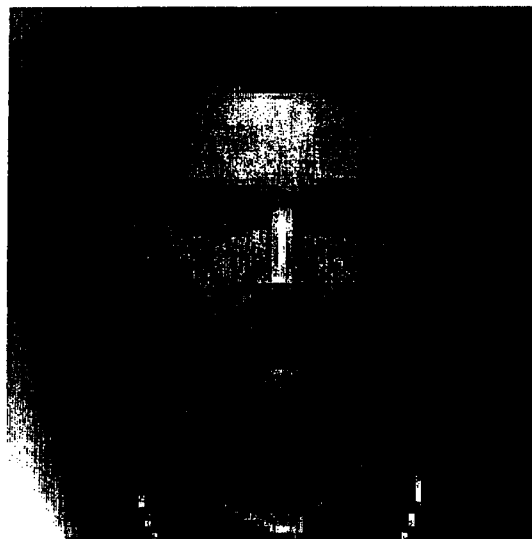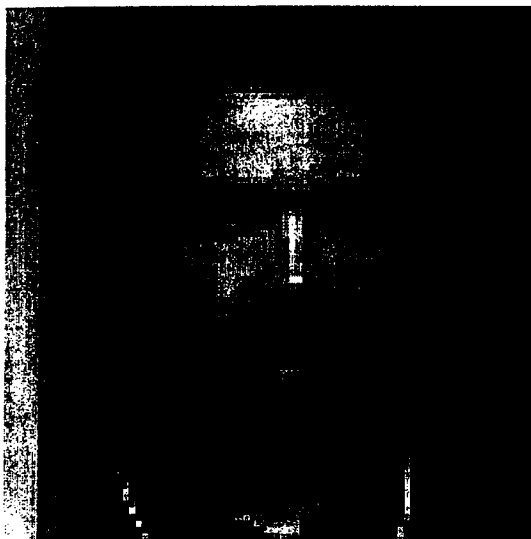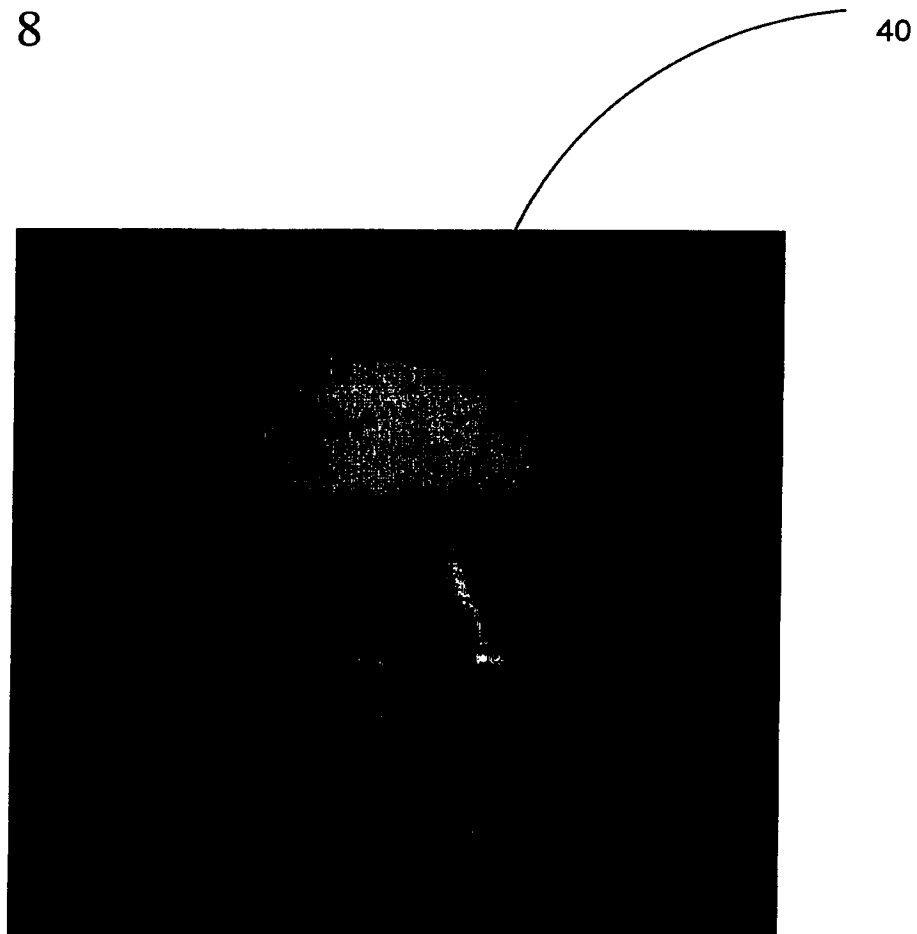
Fig. 2

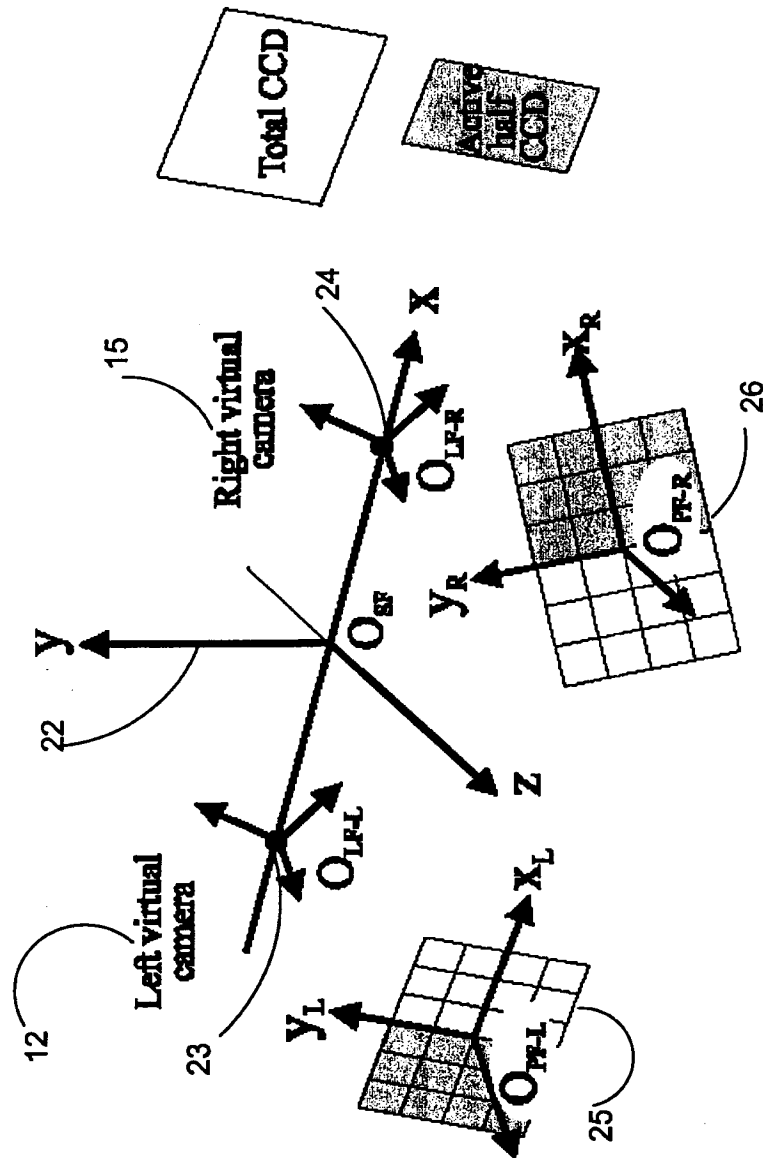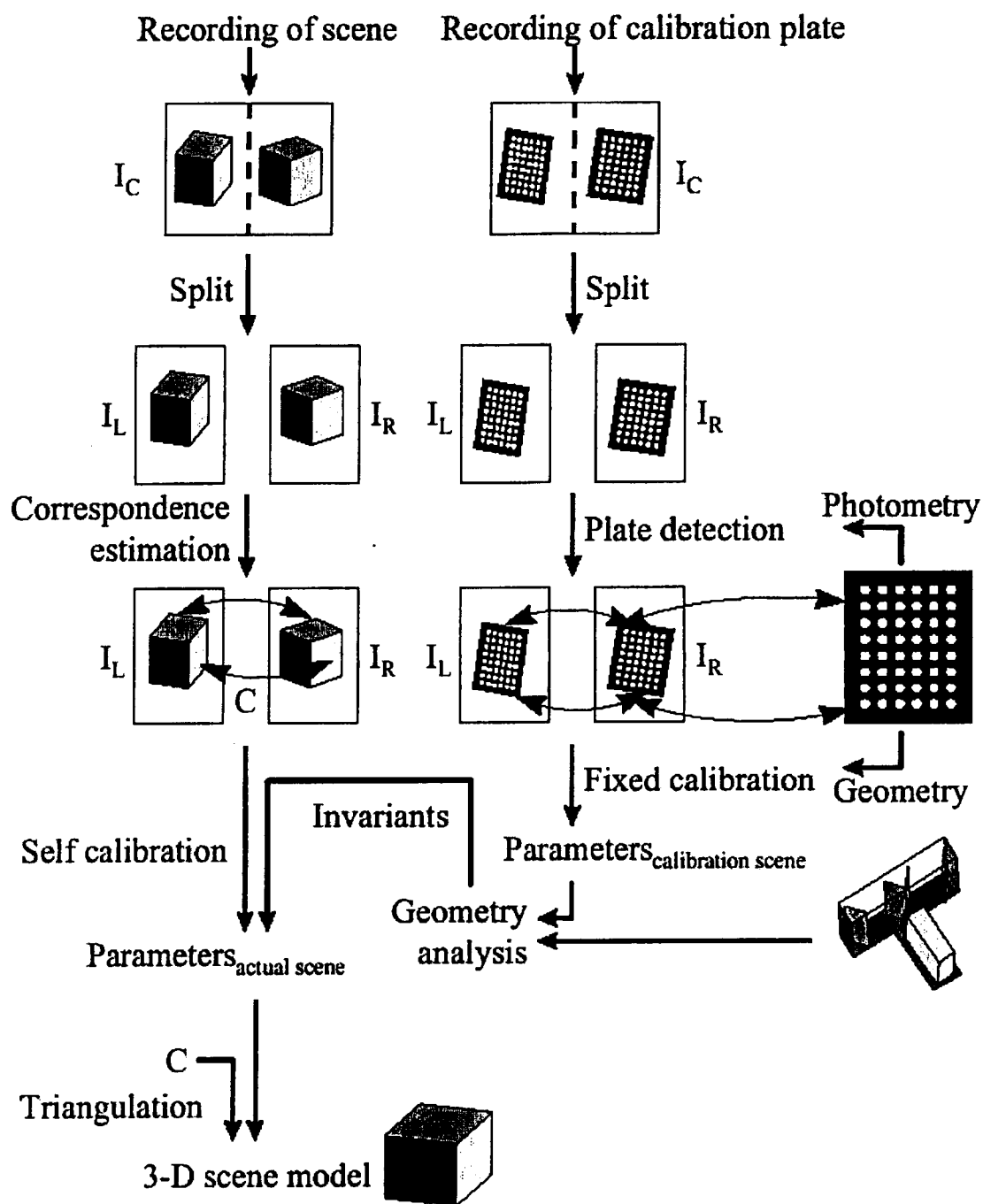Fig. 3

Fig. 4   3/6

Recording of scene   Recording of calibration plate

I_C I_C

Split   Split

I_L I_R I_L I_R

Correspondence   Plate detection   Photometry
estimation

I_L I_R I_L I_R

C

Fixed calibration   Geometry

Invariants

Self calibration   Parameters$_{calibration\ scene}$

Parameters$_{actual\ scene}$ Geometry
                                        analysis

C

Triangulation

3-D scene model

Fig. 5a

Fig. 5b

Fig. 6

Fig. 7

Fig. 8

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INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7   H04N13/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7   H04N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 811 876 A (ZANEN PIETER O) 10 December 1997 (1997-12-10) page 5, column 8, line 36 -page 6, column 10, line 3; figures 5,6	1-20

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
4 September 2000	11/09/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	De Paepe, W

1

INTERNATIONAL SEARCH REPORT

information on patent family members

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
EP 0811876	A	10-12-1997	US	5828913 A	27-10-1998
			US	5883662 A	16-03-1999